Reevaluation of surface rupture parameters and faulting segmentation of the 2001 Kunlunshan earthquake (M w 7.8), northern Tibetan Plateau, China

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[1] The 14 November 2001, M_w = 7.8 Kunlunshan earthquake ruptured the westernmost part of the Kunlun Fault, northern Tibetan Plateau. The main segment affected by this event was the Kusaihu segment. Field investigations allowed us to constrain the length, the width, and the coseismic horizontal displacement distribution of the Kunlunshan earthquake rupture zone. The mapped surface rupture zone starts from 90.257°E in the west and ends at 94.795°E in the east with a total length of 426 km. It consists of three main sections, the western strike-slip section, the transtensional section, and the eastern strike-slip section. The rupture zone is oriented N100° ± 10°E on average. The distribution of the coseismic horizontal displacements is characterized by multiple peaks departing clearly from a general bell-shaped distribution. Reassessment of the maximum coseismic horizontal left-lateral displacement yields a value of 7.6 ± 0.4 m at the site (35.767°N, 93.323°E) consistent with independent measurements derived from interferometric synthetic aperture radar and seismology. From this site the horizontal displacement decreases unevenly to both the west and east. Coseismic vertical (reverse) displacement is also noted at the eastern end of the rupture but it remains much smaller than the horizontal component. The width of the rupture zone varies from site to site from several meters to few kilometers. The maximum width measured reaches 8 km along the Yuxi Feng subsection where a large number of shaking related cracks were well developed.

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1. Introduction

[2] At 1726 LT (0926 UT) on 14 November 2001, the M_w7.8 Kunlunshan earthquake ruptured along the western part of the Kunlun fault. This fault had long been recognized as one of the major left-lateral strike-slip faults bounding the Tibetan Plateau [*Tapponnier and Molnar*, 1977; *Van der Woerd et al.*, 2002; *Lin et al.*, 2002; *Xu et al.*, 2002a; *Song*, 2003]. Surface ruptures of the Kunlunshan earthquake extend over 426 km in total, with azimuth averaging N100° ± 10°E, making these surface ruptures the longest yet observed in the world [*Yeats et al.*, 1997]. From west to east, the surface ruptures can be divided in three distinct sections: a strike-slip section about 26 km long on a secondary strike-slip fault, a transtensional section in a pull-apart basin 50 km long and 10 km wide, and the eastern strike-slip section on the Kusaihu segment about 350 km long (Figure 1).

[3] Earthquake rupture length and maximum coseismic displacement are valuable parameters to describe earthquake surface rupture pattern. Such parameters could be linked to moment magnitude (M_w) through empirical relationships and later use in seismic hazard assessment for similar segmented long active faults [*Wells and Coppersmith*, 1994; *Yeats et al.*, 1997]. Therefore, despite remoteness and high elevation (~4500 m above sea level), many research teams visited the earthquake rupture area soon after the Kunlunshan earthquake and a large amount of data such as coseismic displacements, length of individual rupture segment and width of the faulting zone have been collected [*Lin et al.*, 2002; *Xu et al.*, 2002a; *Dang and Wang*, 2002; *Chen et al.*, 2003; *Klinger et al.*, 2005; *Li et al.*, 2005]. Although these data provide preliminary information to understand the earthquake surface rupture mechanism, some of the rupture parameters, such as the maximum coseismic horizontal displacement, are still under debate [*Xu et al.*, 2002a; *Lin et al.*, 2002, 2004; *Song*, 2003; *Chen et al.*, 2003]. Values proposed for the maximum horizontal displacement range from 16.3 m [*Lin et al.*, 2002] to 6.4 m [*Chen et al.*, 2003]. Better constraint on the maximum slip is however critical to estimate magnitude and maximum coseismic displacement of future earthquakes along the large strike-slip faults in the northern Tibetan Plateau.

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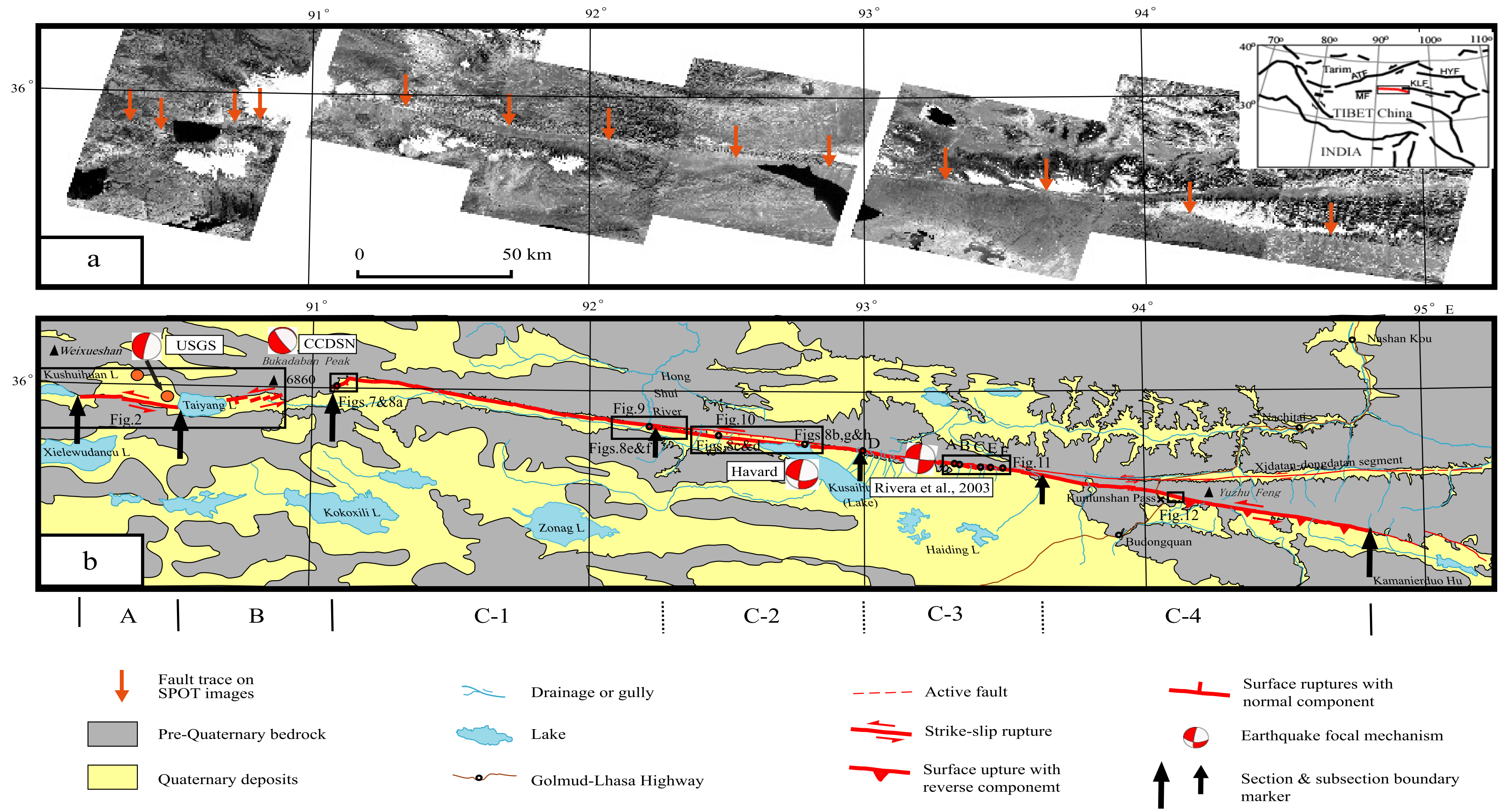

Figure 1. Simplified map of the 2001 Kunlunshan earthquake surface rupture zone on the preexisting fault traces of the westernmost segments of the Kunlun Fault. (a) SPOT mosaic images showing preexisting fault traces of the Kusaihu segment of the Kunlun fault (indicated by red arrows), and inset map at the right upper corner showing locations of the Kusaihu segment (red line) of the Kunlun Fault (KLF), Mani Fault (MF), Altyn Tagh Fault (ATF), and Haiyuan Fault (HYF). (b) Distribution of the 2001 Kunlunshan earthquake surface rupture zone (A,: western strike-slip section; B, transtensional section; C, eastern strike-slip section; C-1, Hongshuihe subsection; C-2, Kusaihu subsection; C-3, Yuxi Feng subsection; C-4, Yuzhu Feng subsection).

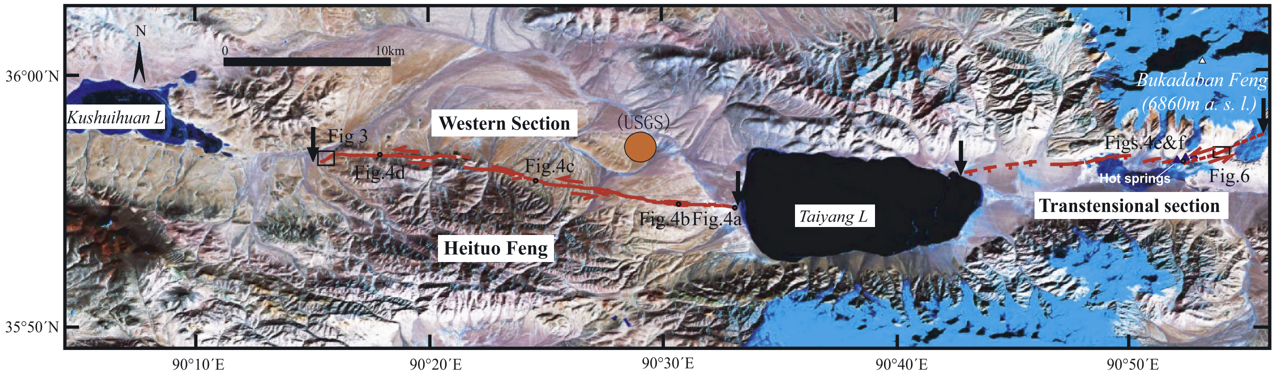

Figure 2. Map showing the surface breaks of the 2001 Kunlunshan earthquake on the western and transtensional sections based on field observations and high-resolution satellite images. Black arrows indicate the terminal point of the surface breaks of the different sections. Blue triangles are hot springs.

[4] Here we present parameters of the Kunlunshan earthquake surface rupture zone derived from both field measurements and interpretations of high-resolution satellite images (Ikonos satellite, pixel resolution 1 m), including a reassessment of the maximum coseismic horizontal displacement, length and width of the surface rupture zone.

2. Earthquake Surface Rupture Pattern

[5] Field investigation and detailed mapping from post-earthquake Ikonos images [*Xu et al.*, 2002b; *Chen et al.*, 2003; *Klinger et al.*, 2005] show that the surface rupture of the Kunlunshan earthquake consists, in first order, of two strike-slip sections, the western section (A) and the eastern section (C), connected by one left-stepping transtensional section (B) (Figure 1). The three sections are described below from west to east.

2.1. Western Section (A)

[6] The western section is about 26 km long (Figure 2). The westernmost surface break is located at 35.959°N, 90.257°E, east of Kushuihuan Lake. From this location, surface breaks extend eastward along the Heituofeng fault to the Taiyang Lake (35.926°N, 90.548°E), where the epicenter was located (U.S. Geological Survey, Rapid moment tensor solution of southern Xinjiang earthquake, China, 2001, available at http://wwweic.eri.u-tokyo.ac.jp/∼cmt/USGS/CMT/0111140926). The Heituofeng fault is a secondary strike-slip fault, which is part of the horsetail fault system that ends the Kunlun fault westward [*Xu et al.*, 2002a; *Van der Woerd et al.*, 2002].

[7] The western end of the rupture, oriented N240°, is characterized by a series of N35° ± 5°E trending en echelon extensional fissures connected by mole tracks (Figure 3). The fissures are 5–25 m long and the mole tracks are 3–10 m long and 5–20 cm high. Eastward, the rupture strikes N105° for about 7 km before it jumps abruptly ∼1.4 km southward to strike N110°. The eastern end of this rupture, along the western shore of the Taiyang Lake, also displays a succession of long extensional fissures (20 to 50 m long and 5 to 50 cm wide) and low mole tracks (<5 m long and 20 to 30 cm high) in between (Figure 4a). Those extensional fissures strike ∼N50°E. In the field we could not observe any evidence for the rupture entering the lake and the shoreline did not appear to be offset during the earthquake.

[8] The western section cuts terrace risers, young gullies and also car tracks anterior to the earthquake (Figures 4b, 4c, and 4d), displaying predominant left-lateral strike-slip motion with some vertical component. In some places, the last rupture clearly overprint a cumulative scarp down to the north by about 1 to 1.5 m. Coseismic horizontal displacement varies from 1.7 ± 0.2 m at the site (35.942°N, 90.411°E) (Figures 4d and 5a) to 4.5 m [*Klinger et al.*, 2005]. At one site (35.932°N, 90.469°E), using a total station, we could measure 3.9 m of horizontal displacement associated to 0.6 m of vertical motion from the offset riser (Figure 4c). Some of the offset car tracks, offering excellent piercing lines, were also measured and show a horizontal offset in the range of 3 to 3.5 m (Figures 5b and 5c).

2.2. Transtensional Section (B)

[9] The transtensional section connects the western to eastern strike-slip sections (Figures 1 and 2). Although surface breaks along this section were already noted [*Klinger et al.*, 2005], here for the first time we report quantitative measurements of coseismic offsets. The ruptures, about 18 km long, are located in a 50-km-long extensional pull-apart basin at the southern front of the ice-capped Bukadaban Feng (6800 m above sea level).

[10] The surface breaks start on the northeastern shore of the Taiyang Lake (35.957°N, 90.716°E), where discontinu-

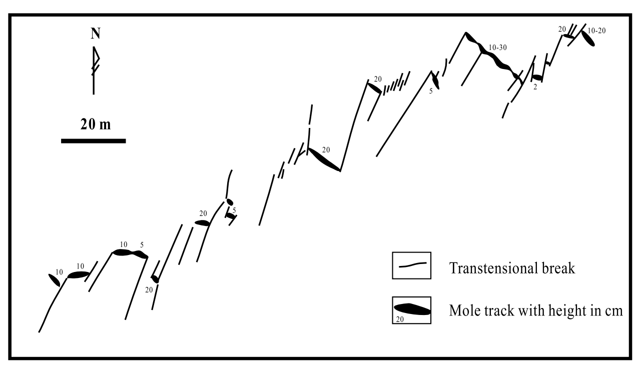

Figure 3. Measured terminal extensional structures for the 2001 Kunlunshan earthquake surface ruptures at the westernmost end of the western strike-slip section east of Kushuihuan Lake (35.959°N, 90.257°E).

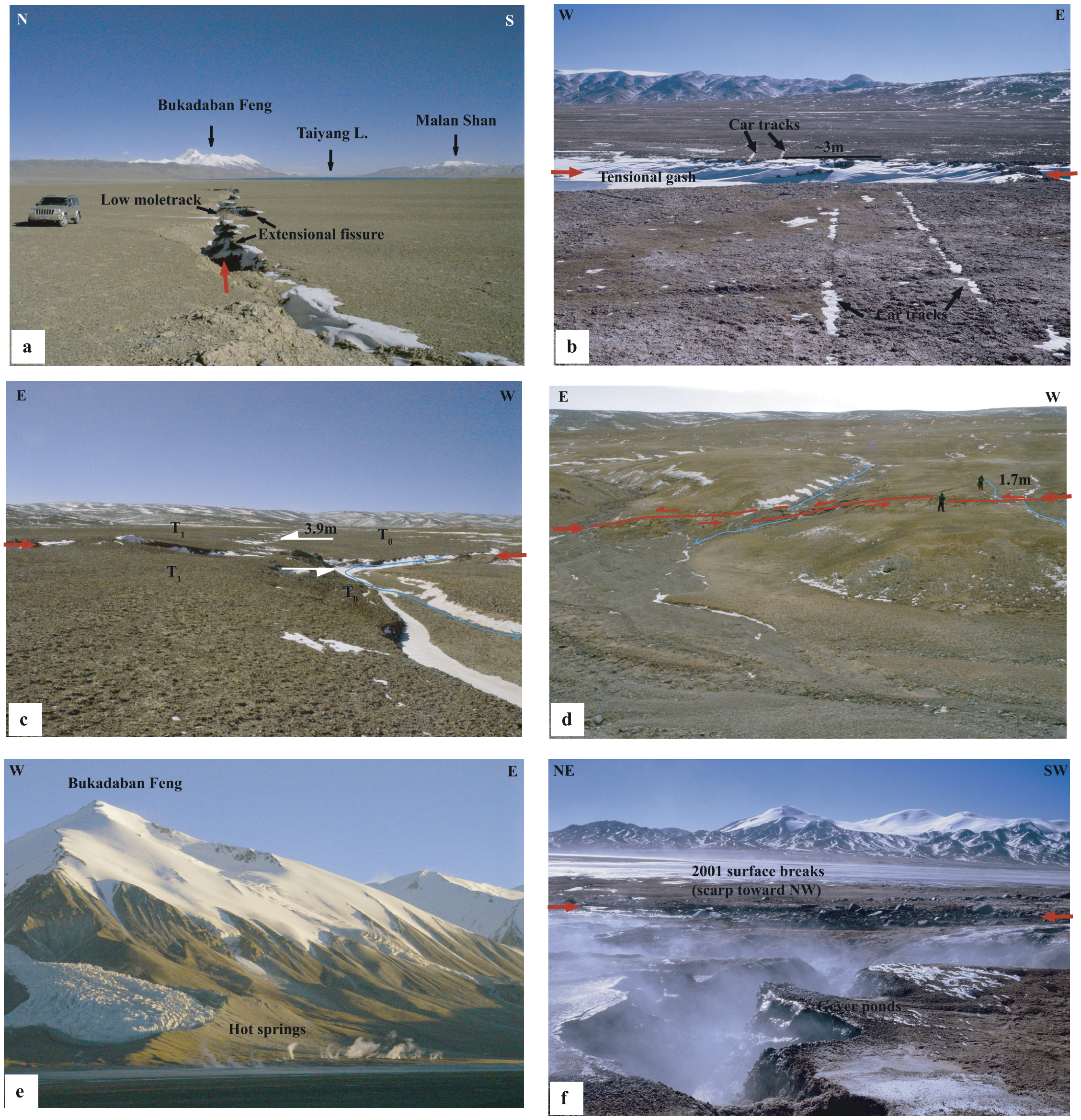

Figure 4. Typical surface breaks on the western strike-slip and transtensional sections of the 2001 Kunlunshan earthquake (see Figure 2 for detailed locations). Red arrows indicate the trend of the surface rupture zone or surface breaks and fine blue line shows the small gully. (a) NE striking en echelon extensional fissures and low mole tracks at the easternmost end of the western section on the western shore of Taiyang Lake (35.926°N, 90.545°E). (b) A 65-cm-wide tension gash that sinistrally offset the car tracks about 3 m (35.925°N, 90.522°E). (c) Surface rupture that sinistrally displaced a riser (T_1/T_0) about 3.9 m (35.932°N, 90.469°E). T_1 is the high/old terrace, while T_0 is the low/young terrace. (d) Offset alluvial fans and two small gullies incising onto it with a left-lateral displacement of about 1.7 m (35.942°N, 90.311°E). (e) View of hot spring fumes from geyser ponds along the southwestern piedmont of Bukadaban Feng. (f) Close-up view of geyser ponds at the site (35.961°N, 90.874°E). Note the ponds occur near to the 2001 earthquake surface breaks.

ous fresh breaks have been identified with vertical down throw of 30 cm to the south and a minor left-lateral component that increases eastward. Right-stepping fissures extend discontinuously eastward across the large alluvial fans that abut the southern front of Bukadaban Feng. Below the main summit of Bukadaban Feng, the surface breaks that strike N65° ± 5°E are well developed. The breaks cross a hydrothermal field about 1.5 km long that was reactivated after the 2001 earthquake, according to locals, although it was already noted on the geological maps. The hydrothermal activity is characterized by vents with surging boiling water and fumes coming out from the freshly opening fissures (Figures 4e and 4f). Even if the hydrothermal field is highly localized, it is clearly associated to the overall extension that is visible in the pull-apart between the western and eastern strike-slip sections south of Bukadaban Feng.

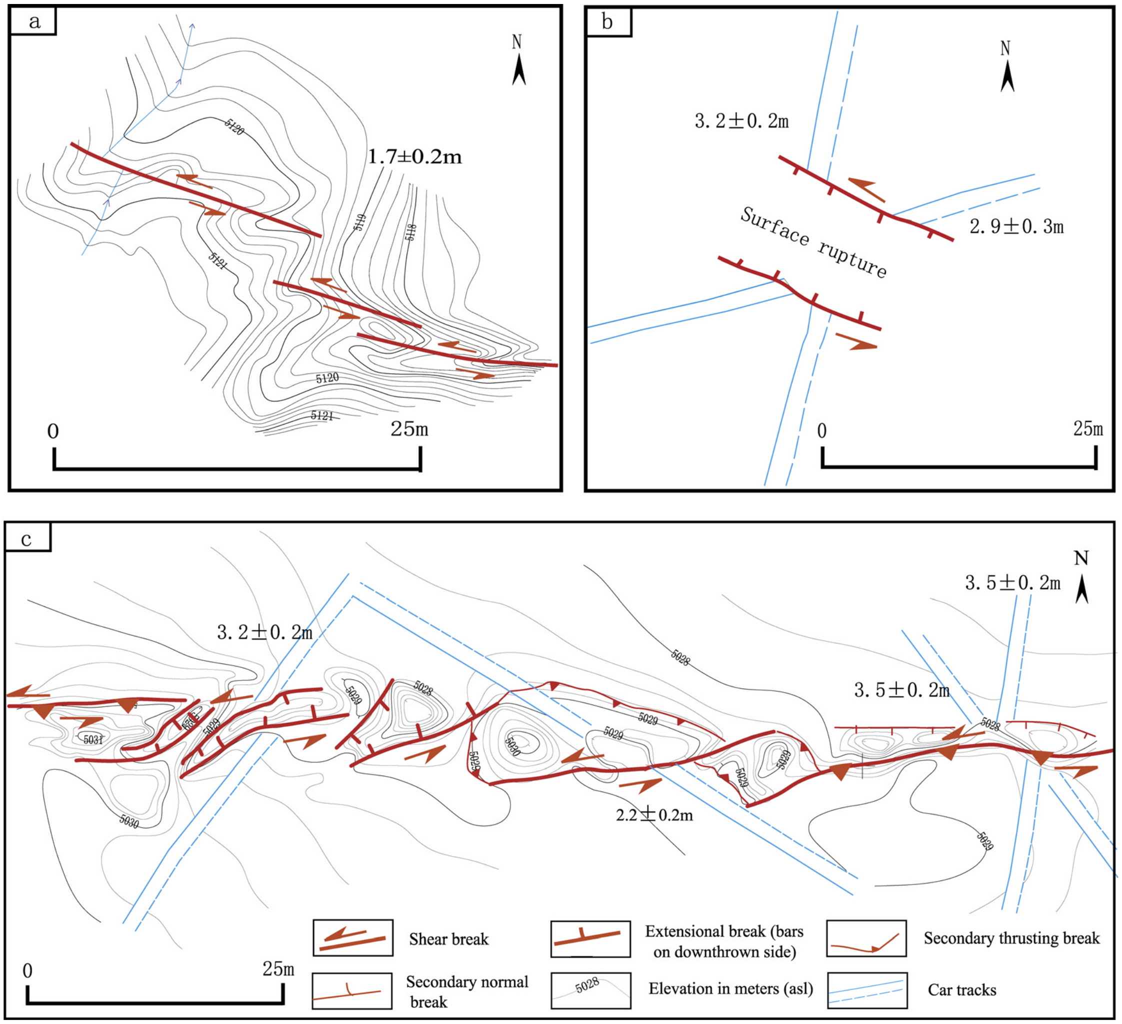

Figure 5. Topographic maps showing surface rupture structures and coseismic left-lateral displacements on the western section (numbers are coseismic horizontal displacements). (a) Right-stepping strike-slip surface breaks and offset alluvial fan and two small gullies incising onto it at the site (35.942°N, 90.411°E). (b) Strike-slip surface breaks with extensional component and offset car tracks at the site (35.925°N, 90.510°E). (c) En echelon strike-slip surface breaks and offset car tracks at the site (35.925°N, 90.522°E).

[11] At the southwestern piedmont of Bukadaban Feng, west of the recent moraines, three different alluvial fan surfaces, a_0, a_1 and a_2 can be identified (Figure 6a). The a_0 surface is characterized by ground surface covered by gravels at the western front of the moraines further east, a_1 surface is characterized by the smooth grassland where one car and a man stood as scales, and a_2 surface is the eroded high grassland where gravels outcrop (Figure 6a). The 2001 rupture is clearly localized along a preexisting cumulative fault scarp. Using total station we measured coseismic deformations and cumulative offsets at a site (35.964°N, 90.888° E) (Figure 6b). On average, the preexisting scarp is about 1.5 ± 0.1 m high across the oldest part of the alluvial fan (a_2), about 0.6 m high across the intermediate part of alluvial fan (a_1) and only the 2001 fresh breaks are visible across the youngest part of the fan (a_0). The 2001 coseismic left-lateral horizontal displacement is 1.5 m, and the vertical throw is 0.3 m down to the north. Thus the rupture could possibly behave following a vertical characteristic slip scheme [*Sieh*, 1996; *Klinger et al.*, 2003; *Liu et al.*, 2004]. In that case it would show evidences across the different part of the fans for four and one similar surface-rupturing events prior to the 2001 earthquake.

[12] Farther east, along the southern piedmont of Bukadanbang Feng, moraines have developed and the 2001 Kunlunshan earthquake surface breaks are unclear. Numerous fresh landslides, however, are aligned along the moraine talus that could have been triggered by the earthquake. Nowhere did we find unambiguous surface breaks at the base of the large triangular facets that bound Bukadanbang Feng. It is therefore possible that along this section the surface rupture did not reach the surface. Extensional surface breaks are visible again at a site (35.989°N, 91.106°E), west of the easternmost glacial lobe at the southeastern piedmont of Bukadaban Feng, where they connect with the eastern section. Thus there is a 20-km-long surface rupture gap between the transtensional section and eastern strike-slip section.

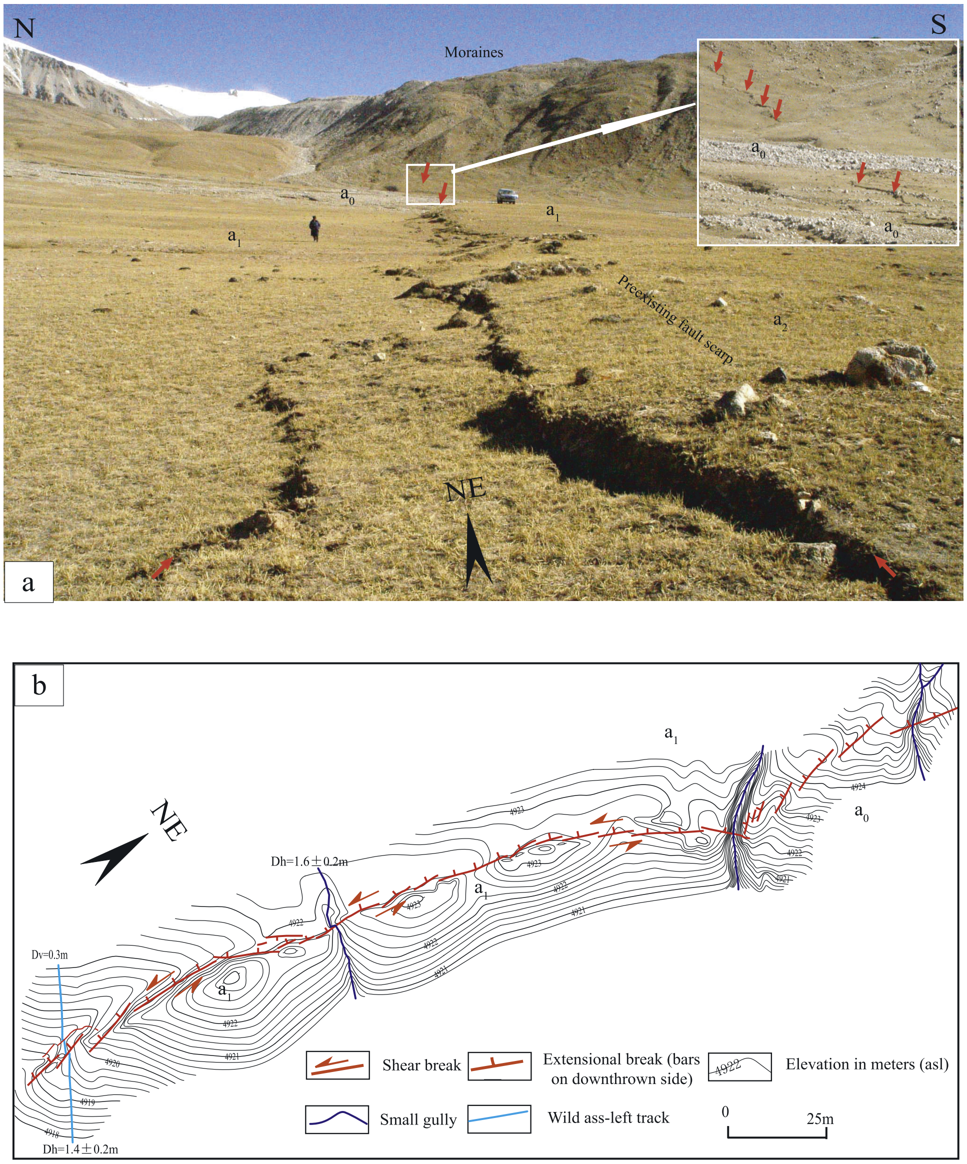

Figure 6. Offset geomorphic features of the 2001 Kunlunshan earthquake at 35.964°N, 90.888° E on the transtensional section. (a) View of the 2001 surface breaks and preexisting fault scarps on different parts of alluvial fan along the southwestern piedmont of Bukadaban Feng. Note the inset at the upper right corner showing the discontinuous surface breaks cutting into the moraines below the main peak of Bukadaban Feng. (b) Topographic map derived from total station measurement showing surface rupture pattern and coseismic left-lateral displacements, as well as the preexisting fault scarp on the different parts of the alluvial fan.

2.3. Eastern Section (C)

[13] The eastern section forms the main surface rupture associated to the Kunlunshan earthquake. Starting at the southeastern piedmont of Bukadaban Feng (35.989°N, 91.016° E), the surface breaks extend east-southeast (N100° ± 10°E) for a distance of 350 km to end at the site (35.556°N, 94.795°E) about 70 km east of the Golmud-Lhasa Highway [*Xu et al.*, 2002b]. This section of the rupture follows the long–time recognized Kusaihu segment of the Kunlun fault. In addition to the 2001 rupture, many evidences for paleoearthquakes have also been reported along this section of the fault, attesting of its important seismic activity in the past [*Earthquake Administration of Qinghai Province*, 1999; *Van der Woerd et al.*, 2000; *Li et al.*, 2005].

[14] On the basis of large-scale geometry and coseismic slip distribution, the eastern section can be divided into 4 subsections, from west to east, the Hongshuihe (C-1), the Kusaihu (C-2), the Yuxi Feng (C-3) and the Yuzhu Feng (C-4) subsections (Figure 1).

2.3.1. Hongshuihe Subsection (C-1)

[15] The Hongshuihe subsection is 115 km long. To the west, it is connected to the transtensional section. To the east, it ends about 6 km east of the outlet of Hongshuihe (35.889°N, 92.283°E), a river that flows north through the Kunlun Range (Figure 1).

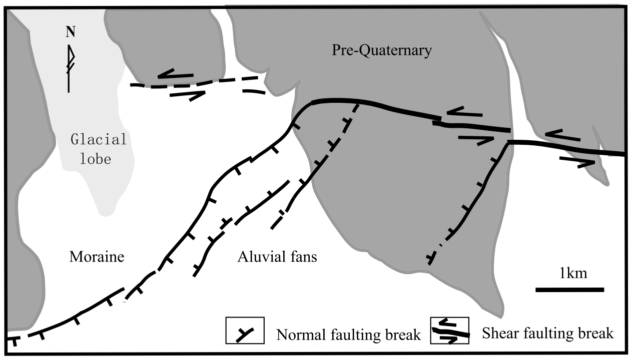

Figure 7. Terminal normal faulting rupture at the westernmost end of the eastern strike-slip section, southeastern piedmont of Bukadaban Feng (35.989°N, 91.016°E).

[16] The western end of the subsection is characterized by two sets of extensional fissures facing each other (Figure 7). These fissures, extending westward to the terminal point (35.989°N, 91.016°E), are oriented ∼115° clockwise relative to the average N100° ± 10°E strike of the Kusaihu segment. They form a small graben about 1000 m wide that crosscuts recent moraines from Bukadaban Feng glacier and alluvial fans. At one site (36.004°N, 91.106°E) we could measure the northern extensional fissure to form a south facing fault scarp about 1–1.5 m high with 1 to 2 m of opening (Figure 8a).

[17] Except at its western end, the Hongshuihe subsection is characterized by localized left-lateral strike-slip faulting with only minor vertical motion. This subsection displays typical strike-slip rupture morphology as a series of linear segments connected by mole tracks or tension gashes, depending on the geometry of the relay zone (Figure 9a). In many places, streams, alluvial fans and terrace risers are offset sharply, allowing accurate measurements of coseismic horizontal displacements (Figure 9b). Typical coseismic horizontal displacements along this subsection are in the range of 3 to 5 m [*Klinger et al.*, 2005]. At one site (35.893°N, 92.159°E) about 6 km west of the outlet of Hongshuihe River, where two south flowing gullies join (arrow-marked site in Figure 9a), several terrace risers and gullies incising into those terraces allowed us to measure the 2001 earthquake horizontal displacements and also cumulative offsets. The most recent displacement is measured as 3 m from the offset young riser and a cumulative horizontal offset about 6 m from the offset old riser. Such repeated observations along the Hongshuihe subsection strongly suggest that this subsection has a slip characteristic behavior for occurrence of surface rupturing earthquakes [*Klinger et al.*, 2005; *Li et al.*, 2005; *Liu et al.*, 2004; *Sieh*, 1996].

2.3.2. Kusaihu Subsection (C-2)

[18] The Kusaihu subsection starts at the outlet of Hongshuihe River (35.872°N, 92.225°E) and extends for about 76 km eastward, striking on average N95° ± 5°E (Figure 1). It ends at 35.814°N, 92.950°E. The beginning of this section in the west is characterized by an ill-defined surface rupture (Figure 9) that splits in two subparallel segments eastward [*Klinger et al.*, 2005]. These two fault traces coexist for about 60 km before they join in a single strand again. The southern strand that cuts through bajadas and fan surfaces exhibits almost pure strike-slip motion with typical associated morphology. The northern strand is located at the base of the Kunlun range front, about 2 km north from the southern strand, and exhibits mainly normal faulting with vertical motion in the range of 0.5 to 1 m. This peculiar geometry has been interpreted as due to slip partitioning between the horizontal and vertical slip components when the rupture reaches to the surface [*King et al.*, 2005].

[19] The normal faulting strand, segmented and discontinuous, is located at the base of large triangular facets several hundred meters high (Figure 8b). Short normal scarps are also visible between the normal and the strike-slip faulting strands (Figure 10). From the Ikonos images, however, it is clear that only some of those scarps were reactivated during the 2001 earthquake. These scarps are oblique to the strike-slip strand and curve to align with the normal strand to the north. They correspond to zones where none of the two regimes dominates enough to allow formation of long-term active features [*King et al.*, 2005; *Klinger et al.*, 2005].

[20] The strike-slip faulting strand shows almost no evidence of significant vertical motion that could affect south flowing drainages from the southern Kunlun Range. However, at one site (35.851°N, 92.479°E) vertical slip is noticeable. There, a north facing cumulative fault scarp has clearly developed that blocks southward flowing drainages to form a large sag pond (Figures 8c and 10). Two coseismic left-lateral offsets of 2.7 and 2.8 m have been measured from two offset gullies incising into the scarp (Figure 8d). Although the cumulative vertical scarp is 6.5 m in height, the coseismic vertical motion is only 0.4 m. Besides, the surface breaks sinistrally cut several risers at its western end near the outlet of Hongshuihe River (Figure 8e). There the earthquake fault dips toward the north and cuts the Neogene

Figure 8. Typical surface breaks on the Hongshuihe and Kusaihu subsections of the eastern strike-slip section (see Figure 1 for detailed locations). Red arrows indicate the trend of the surface rupture zone or surface breaks and fine blue line shows the small gully. (a) Normal faulting scarp about 1.5 m high at the southeastern piedmont of Bukadaban Feng (36.004°N, 91.106°E) showing the terminal extensional fissures on the Hongshuihe subsection. (b) Offset shoreline beach ridge along the northern Kusaihu Lake and normal faulting scarps in front of the triangular facets (35.830°N, 92.703° E) on the Kusaihu subsection. (c) North facing fault scarp blocking the south flowing drainages to form a large sag pond west of Kusaihu Lake (35.851°N, 92.479°E). (d) The 2001 surface breaks overprinted on the north facing fault scarp at the same site as Figure 8c. (e) View of the offset terraces at the southern outlet of Hongshuihe River (35.871°N, 92.226°E) on the western end of the Kusaihu subsection. (f) Outcrop of the earthquake fault that cut the young terrace riser (T_1/T_0) at the same site as Figure 8e. (g) View of the 2001 normal scarp overprinted on the northern fault scarp of the pull-apart basin and strike-slip breaks in the basin (35.830°N, 92.697° E). (h) Subparallel shaking-related cracks stepping down to the south north of Kusaihu Lake (35.831°N, 92.696°E).

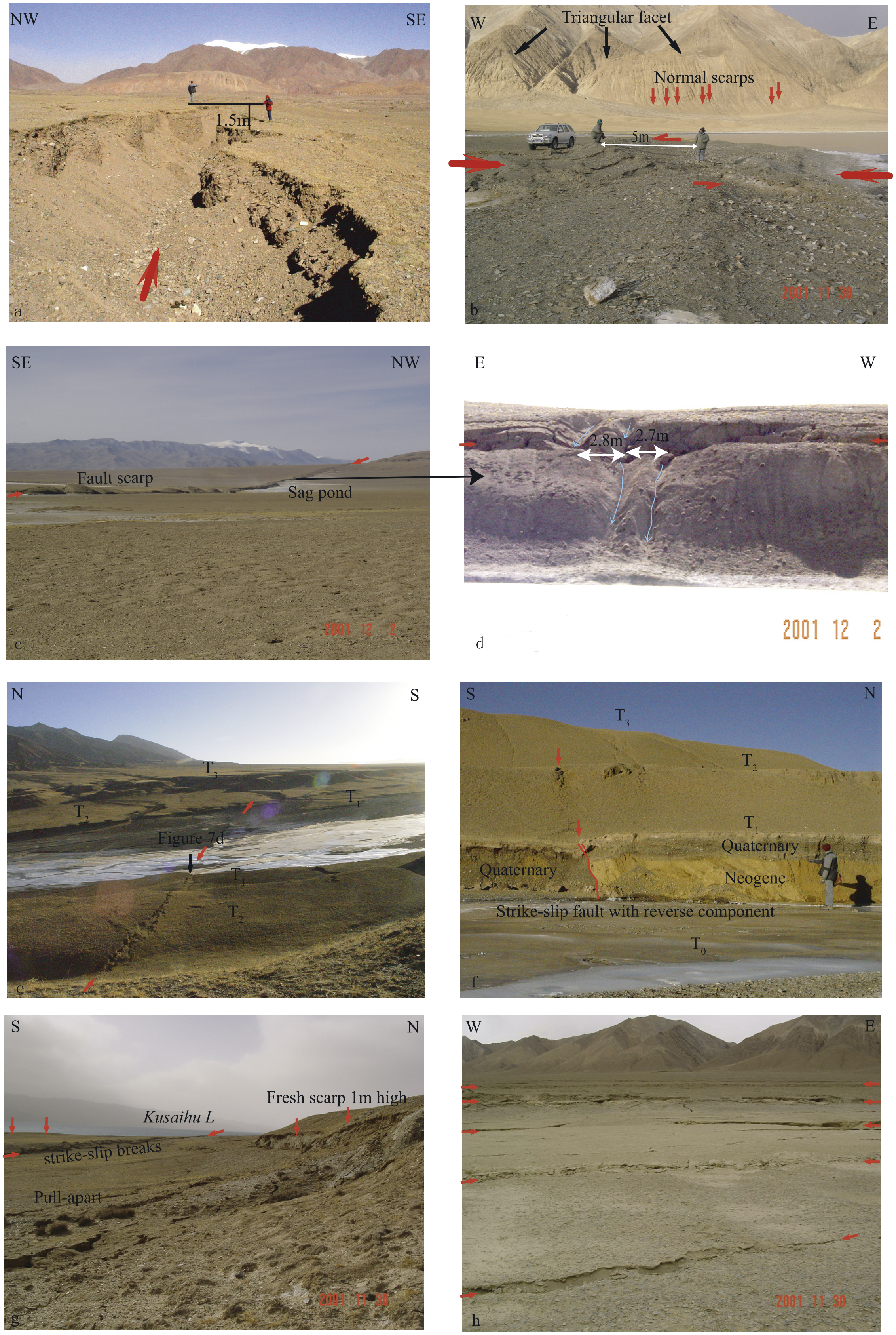
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Figure 8

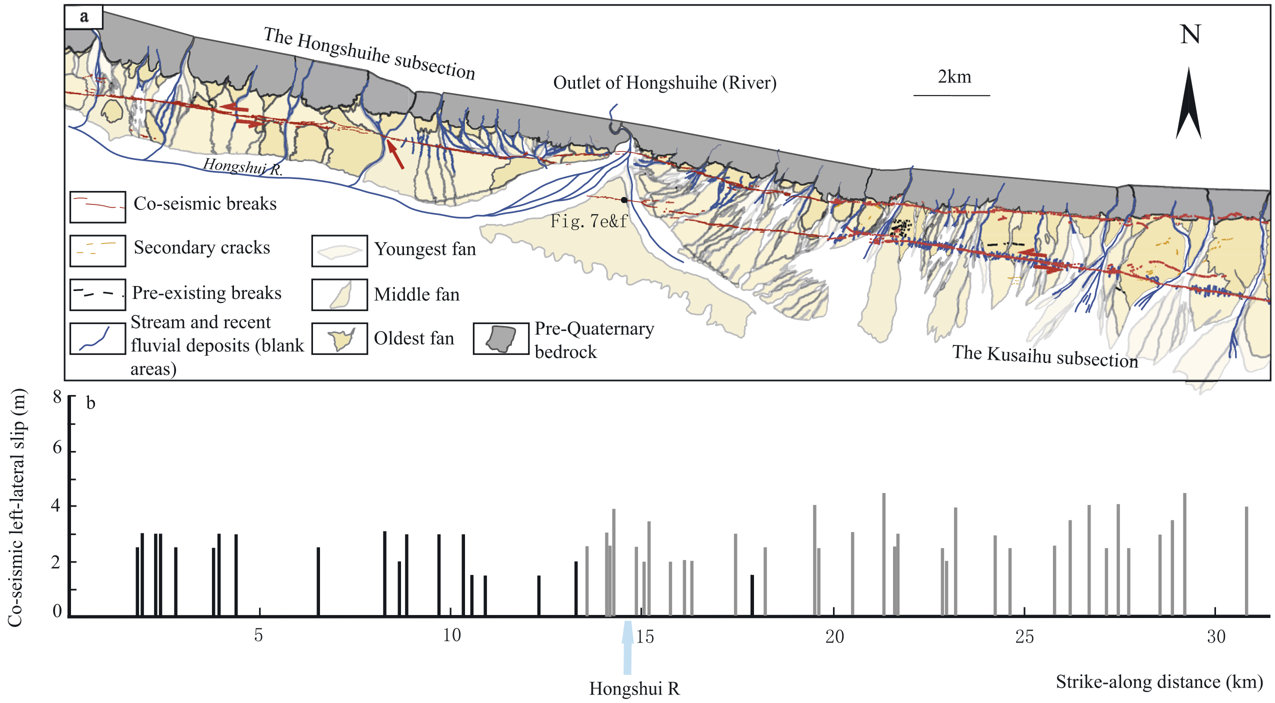

Figure 9. Surface rupture pattern around the step over between the Hongshuihe and Kusaihu subsections nearby the outlet of Hongshuihe River. Note that the coseismic horizontal displacement on the Hongshuihe subsection disappears sharply at the step over east of the outlet of Hongshuihe River. (a) Distribution of the coseismic surface break strands that cut streams/gullies, terraces, and postglacial fluvial fans at the southern piedmont of Kunlun Range (after *Klinger et al.* [2005] and modified). (b) Strike-along variation of the coseismic left-lateral displacements on the Hongshuihe subsection (black lines) and on the Kusaihu subsection (grey lines) derived from Ikonos images and field measurements.

and Quaternary, showing its northern wall up with a reverse component (Figure 8f).

[21] A large cumulative pull-apart basin (about 600 m long, 120 m wide and 20 m deep) has developed along the Kusaihu subsection (35.830°N, 92.697°E). Both normal and strike-slip ruptures could be observed in the basin due the Kunlunshan earthquake. In the field, we could measure 1.9 m of vertical throw on the southern normal bounding fault and about 1 m on the northern flank. Strike-slip motion is localized in the center of the basin, along its longest

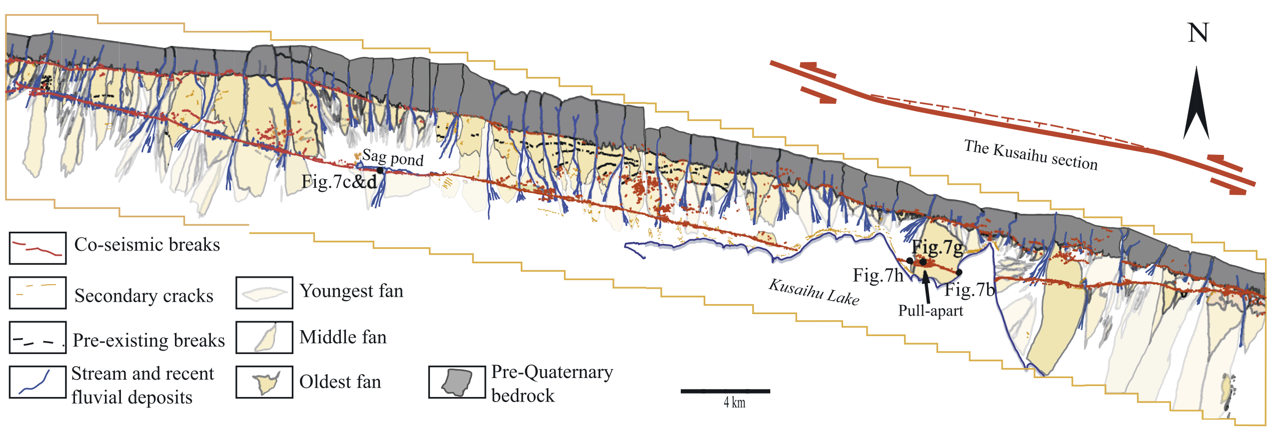

Figure 10. Detailed strip map of the Kusaihu subsection north of Kusaihu Lake from 92.225°E to 92.950°E by using Ikonos satellite images with 1-m-scale resolution, showing the southern purely strike-slip and northern normal faulting strands, and all significant coseismic scarps, cracks, jogs, pull-aparts, push-ups. Inset map shows formation of the normal faulting strand in the dilatational jog on the Kusaihu segment north of Kusaihu Lake owing to left-lateral slip along the farther western and eastern strike-slip strands. Short black lines represent preexisting normal fault scarps that were not reactivated during the 2001 earthquake (modified from *Klinger et al.* [2005]).

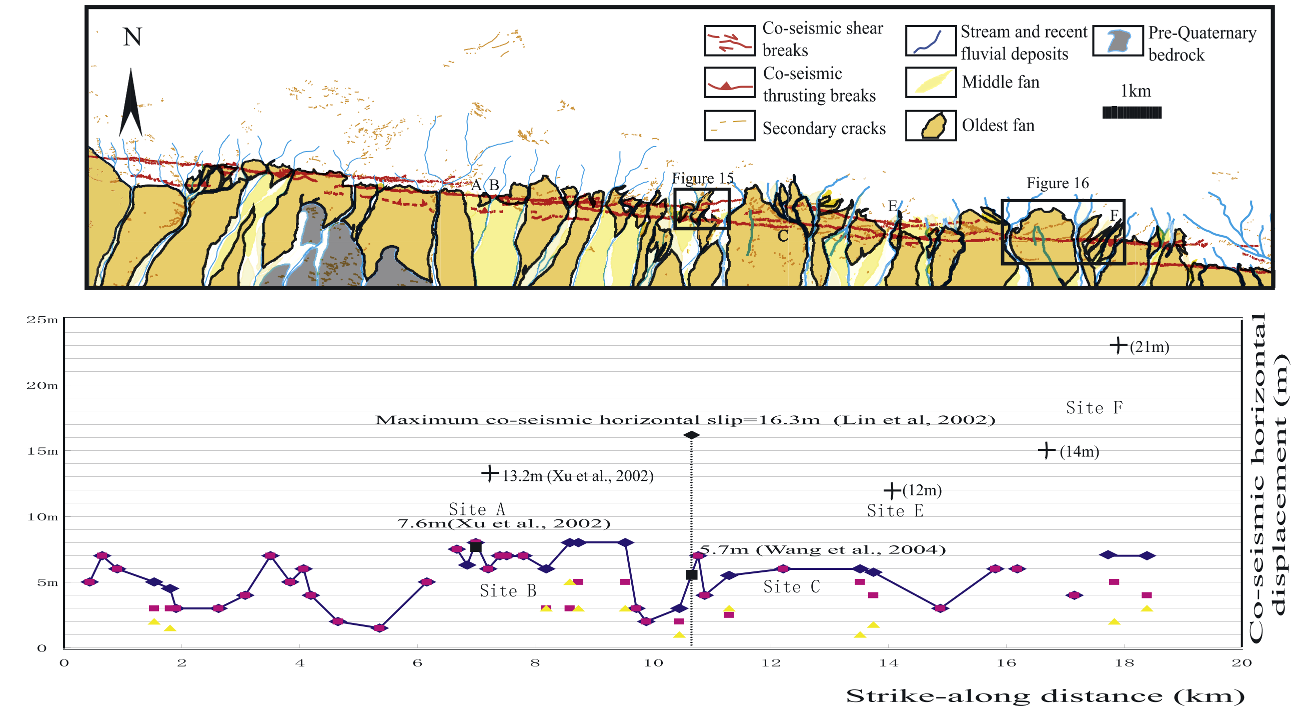

Figure 11. (a) Detailed strip map of the Yuxi Feng subsection of the Kunlunshan earthquake surface rupture zone northeast of Kusaihu Lake from 93.2500°E to 93.4667°E derived from Ikonos satellite images, showing a complicated structure of multiple subparallel strike-slip faulting strands with a reverse faulting strand on the south to form as wide as 550 m surface rupture zone produced directly by faulting (blank areas north of the surface rupture zone are pre-Quaternary bedrocks of Kunlun Range and black square is the location for Figures 15 and 16). (b) Coseismic left-lateral displacements identified from linear geomorphic markers on the Ikonos images and also field measurements. Yellow triangle or mauve square represents coseismic displacement on the single strand and blue rhombus the sum of the coseismic displacements on the different strands at the same site. Black cross represents the cumulative offset value.

diagonal (Figure 8g). In addition, a large number of distributed tensile cracks subparallel to the northern shoreline of the Kusaihu Lake have been observed that step down to the south (Figure 8h), where the strike-slip faulting strand enters the lake. These are probably secondary ruptures created by local strong shaking.

[22] From the eastern shoreline of the lake to the junction of the strike-slip strand to the normal strand (35.806°N, 92.950°E), about 12 km eastward from the lake, the strike-slip strand remains rather simple. The junction between the two strands is characterized by a bend of the fault and could be considered as segment boundary (Figure 1).

2.3.3. Yuxi Feng Subsection (C-3)

[23] From the junction between the two strands of the Kusaihu subsection, the Yuxi Feng subsection extends eastward to Dahong River (35.848°N, 93.513°E), striking on average N100° ± 5°E. The length of this subsection is ~60 km (Figure 1). At the outlet of Dahong River, the rupture bends ~6° southward. It is also at the outlet of Dahong River that the Xidatan-Dongdatan segment of the Kunlun fault branches out from the Kunlunshan earthquake fault. It is noticeable that even the Xidatan-Dongdatan segment is the main continuation of the Kunlun fault eastward; no coseismic displacement was triggered on this segment.

[24] The surface ruptures along this subsection consist of multiple subparallel fault strands tens to several hundred of meters apart that form a surface rupture zone as wide as 550 m at the southern piedmont of Kunlunshan Range [*Xu et al.*, 2002b]. Most of the strands are strike slip that could overlap for more than 2 km. Locally, a little thrusting component has been observed with a south facing scarp ~0.5 m high. In addition, a large number of shaking-related cracks distributed in the range of 3–4 km have been observed to the south of the surface rupture zone (Figure 11). Thus, in total the width of the coseismic ruptures and the shaking-related cracks together may reach 8 km along this subsection. One possible explanation for such a large width might be the conjunction of the large coseismic slip and the presence of permafrost [*Lin et al.*, 2004]. Hence the frozen ground hampered any folding or plastic deformation and made all the deformation fragile. It is clear, from the different teams involved in the Kunlunshan earthquake study [*Lin et al.*, 2002, *Xu et al.*, 2002b; *Dang and Wang*, 2002; *Chen et al.*, 2003; *Klinger et al.*, 2005; *Lasserre et al.*, 2005], that this subsection bears the maximum coseismic slip, even if the exact amount of horizontal displacement is still under debate (see discussion below).

2.3.4. Yuzhu Feng Subsection (C-4)

[25] This subsection starts east of Dahong River and extends for about 112 km to the east and ends at the site

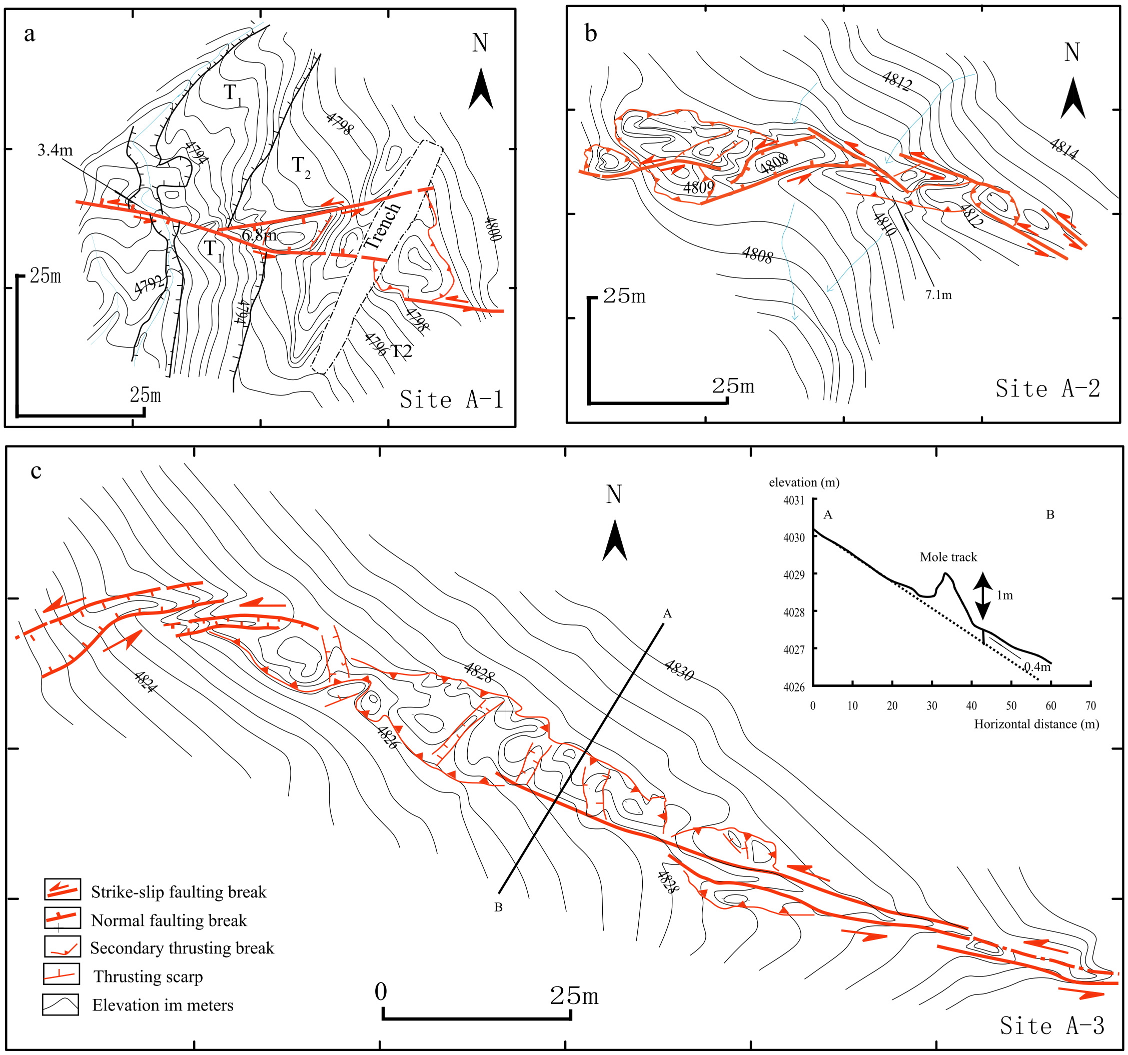

Figure 12. Measured topographic map showing surface rupture pattern and coseismic left-lateral offset features on the Yuzhu Feng subsection. (a) Offset terrace risers at the site A-1 (35.668°N, 94.070°E). (b) En echelon strike-slip breaks, mole tracks and pull-aparts, as well as the offset fan surface and small gullies at site A-2 (35.668°N, 94.069°E). (c) En echelon strike-slip breaks, mole tracks and pull-aparts, as well as the offset fan surface at the site A-3 (35.668°N, 94.0727°E). The inset map shows cross section of a mole track and southern wall up.

(35.55°N, 94.800°E) about 70 km east of the Kunlun pass (Figure 1). The average azimuth is N106° ± 5°E. The surface ruptures are well localized along a preexisting fault, being no more than 20 m wide in most cases. The rupture is characterized by short strike-slip segments with some thrusting and tensile breaks displaying typical en echelon pattern. Field measurement of an offset channel yields a coseismic horizontal displacement of 3.4 ± 0.2 m in left-lateral sense, while a cumulative horizontal offset of the riser is about 6.8 m at site A-1 (35.668°N, 94.070°E) (Figure 12a). A similar cumulative offset from a gully on an alluvial fan is also measured to be 7.1 m at site A-2 (35.668°N, 94.069°E) (Figure 12b). Such repeated observations along the Yuzhu Feng subsection also strongly suggest that this subsection has a slip characteristic behavior [*Klinger et al.*, 2005; *Li et al.*, 2005; *Liu et al.*, 2004; *Sieh*, 1996]. Some WNW trending short thrusting breaks are also observed in the field. Topographic profile across the surface rupture zone at site A-3 (35.668°N, 94.0727°E) shows that the coseismic vertical (reverse) displacement reaches 0.4 m (southern wall up) with pressure ridges about 1.0 ± 0.4 m high that accommodate a local reverse component (Figure 12c). East of 94.80°E, 35.556°N, the surface ruptures bend from N106° ± 5° to N75°E and they consist of en echelon N60° E trending saw-like tensile cracks and low mole tracks that mark the eastern end of the rupture zone.

3. Coseismic Slip Distribution

3.1. Maximum Horizontal Displacement

[26] The maximum coseismic horizontal displacement we could measure in the field is 7.6 m. This maximum value is measured at site A (35.767°N, 93.323°E) along the Yuxi Feng subsection (Figure 1). There the ENE trending en echelon rupture crosses a south flowing gully and adjacent alluvial fans. At this site we measured a left-lateral offset of

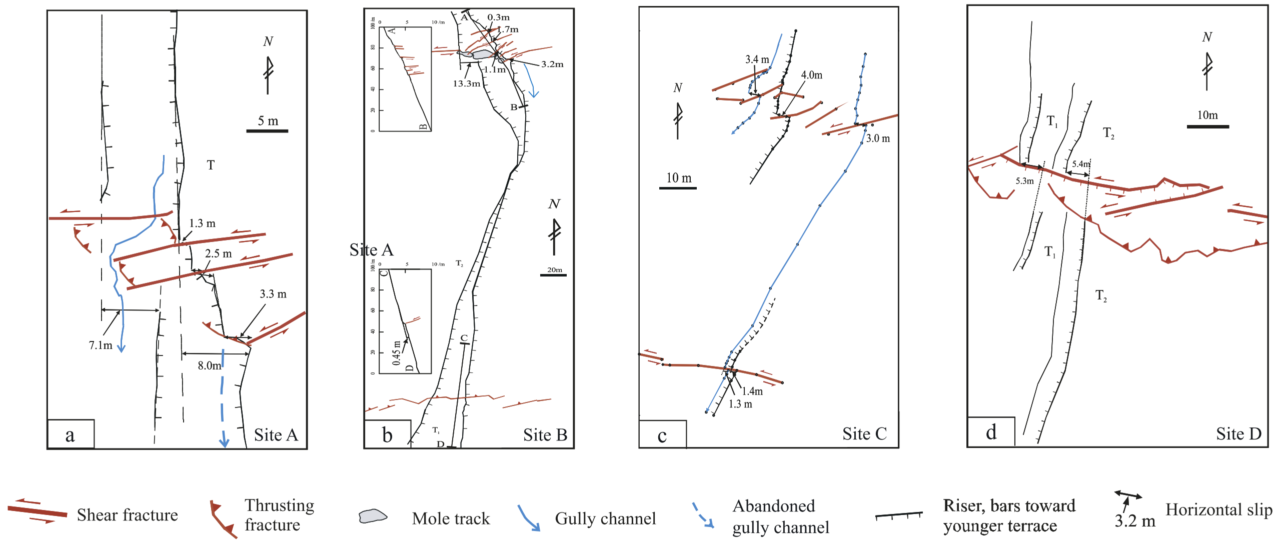

Figure 13. Measured topographic map showing surface rupture pattern and coseismic left-lateral and vertical displacements on the Yuxi Feng subsection (locations are marked in Figures 1b and 11). (a) Site A (35.767°N, 93.323°E). (b) Site B (35.767°N, 93.325°E). (c) Site C (35.762°N, 93.398°E). (d) Site D (35.814°N, 92.955°E).

7.1 m along the western riser of the gully and a 8 m offset along the eastern riser of the gully (Figure 13a), yielding an average coseismic horizontal displacement of 7.6 m. From this site the horizontal displacement decreases unevenly both eastward and westward. At site B (35.767°N, 93.325°E) about 200 m east of the site A, we could measure another offset gully. At this site the rupture displays two main strands, a northern strike-slip strand and a southern thrust strand (Figures 11 and 13b). The northern strand, 35 m wide, is formed by six en echelon transtensional breaks with a general strike of N85°E. The total horizontal displacement measured from the offset youngest riser (T_1/T_0, from the active stream channel T_0 to the youngest abandoned terrace T_1) is 6.3 m. As the measurement was done during the winter of year 2001, just after the earthquake, when freezing reduces water flow almost to zero, the chances that the terrace riser has been already partially eroded are very low. Therefore we do not consider that we underestimate the actual coseismic displacement significantly. At this site we could also measure a cumulative horizontal displacement from the offset riser T_2/T_1, which is 13.2 ± 0.2 m. In this case we argue it is only a minimal value due to possible partial erosion of the riser located south of the rupture caused by water flowing at the T_1 surface, before T_1 got incised to form the current streambed T_0. Across the southern thrusting strand we measured a vertical displacement of ~0.45 m. Measurements at site C (35.762°N, 93.398°E), where ruptures are formed by two strands, yields a total horizontal displacement of 5.9 ± 0.5 m (Figure 13c). Finally, a similar horizontal displacement of ~5.4 m is obtained at site D (35.814°N, 92.955°E) (Figure 13d).

[27] Those measurements, incorporated with other coseismic displacement data we collected in the field and from satellite images, are displayed in Figure 14. It shows that the maximum horizontal coseismic displacement due to the

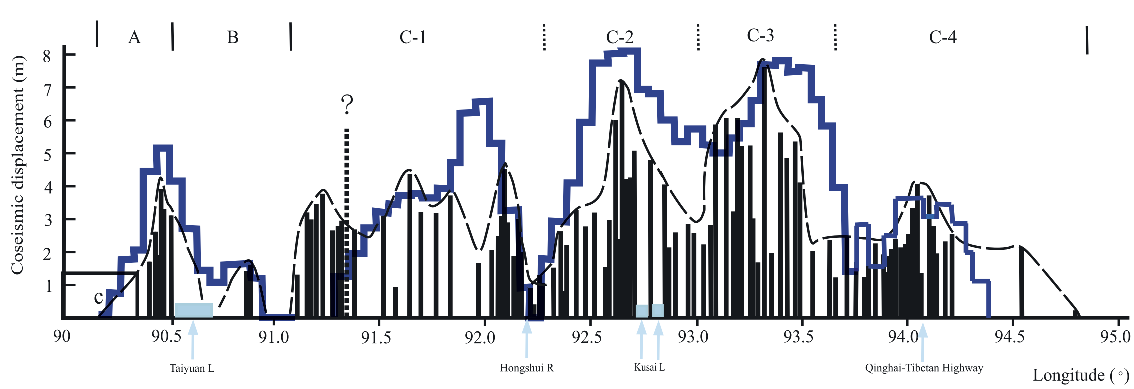

Figure 14. Distribution of the measured horizontal coseismic horizontal displacements along the strike of the surface rupture zone. Blue lines represent the coseismic horizontal displacements inferred from INSAR data [*Lasserre et al.*, 2005]. Other legends are the same as in Figure 1. Horizontal displacements are collected from *Xu et al.* [2002b], *Dang and Wang* [2002], *Chen et al.* [2003], and also measurements in the field.

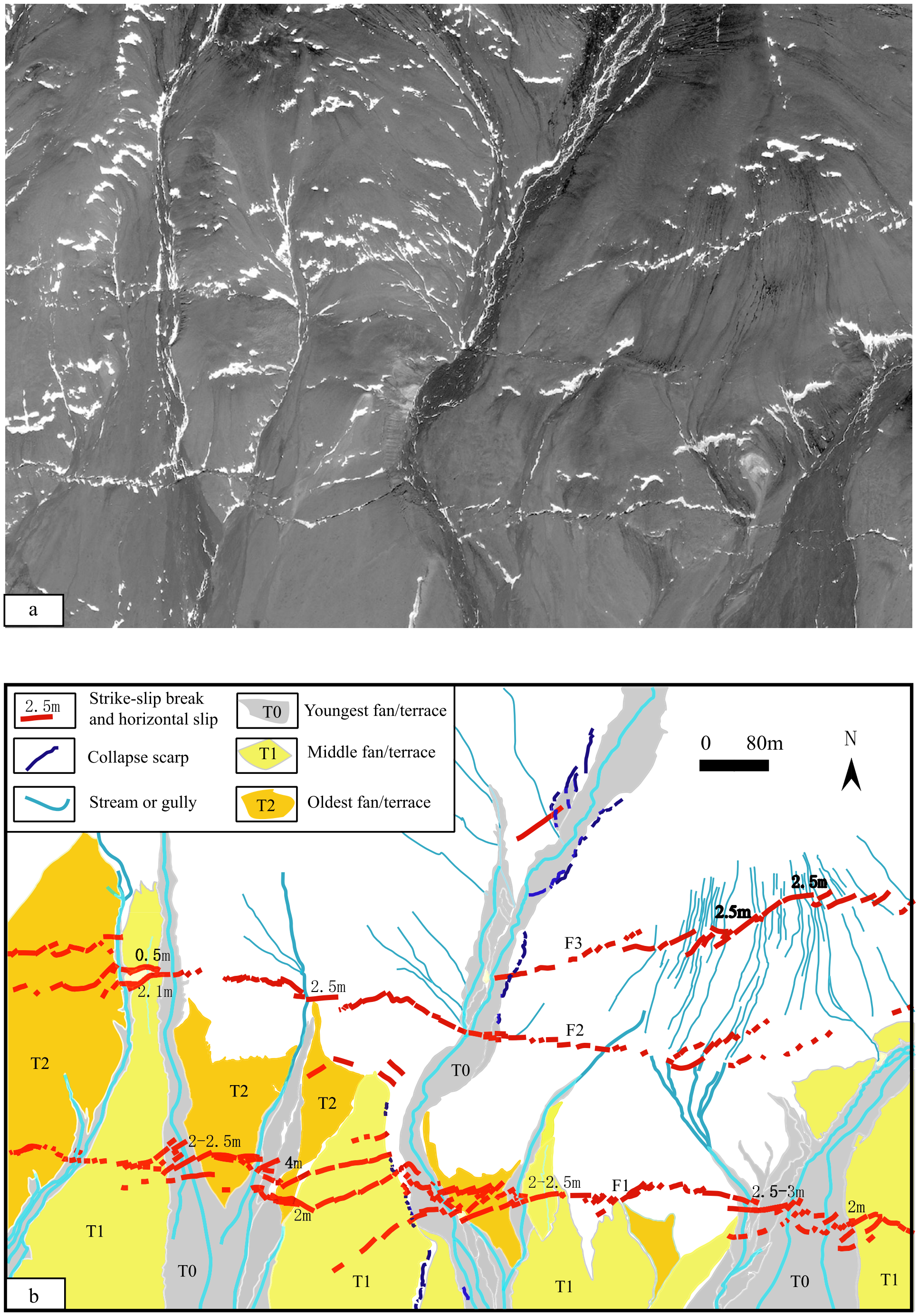

Figure 15. (a) Ikonos image created on 6 January 2003, around the site 93.365°E where *Lin et al.* [2002] gave a maximum coseismic horizontal displacement of 16.3 m. (b) Detailed strip map showing the surface rupture pattern of the Kunlunshan earthquake and coseismic horizontal displacements on different rupture strands. Blank areas are the pre-Quaternary of Kunlun Range.

2001 Kunlunshan earthquake is 7.6 m with an average horizontal one of 4–5. This maximum coseismic horizontal displacement is quite different from the value reported earlier by *Lin et al.* [2002], who have proposed that the maximum displacement was 16.3 m measured across a large gully located at a site 35.762°N, 93.365°E. We argue that this site is not suitable for measuring the coseismic horizontal displacement, owing to a complicated surface rupture pattern that makes any field measurement difficult. From Ikonos satellite images we could map this site in detail (Figure 15). There the rupture consists mainly of three subparallel strands (F_1, F_2 and F_3). The southernmost one (F_1) has the most complicated geometry. Measurements of several offset piercing lines across this fault yield the coseismic horizontal displacements from 2 to 3 m. Similarly, the coseismic horizontal displacements measured from the offset linear geomorphic markers are only ~2.5 m for the middle (F_2) and northern (F_3) strands. Thus the total horizontal displacement at this site should be in the range of 5–6 m identified from the high-resolution image (Figure 15). Here, it should be noted that the horizontal displacement measured from the satellite images is usually larger than that measured in the field [*Klinger et al.*, 2005], probably due to the difficulty of measuring off-fault displacement in the field [*Rockwell et al.*, 2002], bringing our measurement as an upper bound for the actual coseismic horizontal displacement at this site. However, the value of 5–6 m is in agreement with our field measurements at sites A, B and C, all located nearby (Figure 11) and with a field measurement of 5.7 m reported by *Wang et al.* [2004] for the same location. Most probably the 16.3 m offset corresponds to a cumulative displacement, which was not always decipherable in the field due to the harsh field conditions that prevail along the 2001 Kunlunshan earthquake ruptures. On the basis of the same reasoning, we argue the 13.5 m offset reported by the same team few km east of the alleged 16.3 m offset suffers the same kind of misinterpretation. In this case again, all independent measurements (field, interferometric synthetic aperture radar (InSAR), optic correlation, seismology) are coherent in showing a limited coseismic horizontal displacement about 8 m (Figure 14). We feel quite confident in our interpretation as we did also measure several offsets larger than 12 m in the same areas that we demonstrated to be clearly associated to the cumulative offsets. In this area the rupture is composed of subparallel or en echelon strands and offsets many landforms, including drainage networks and terrace risers. Those offset drainage networks and terrace risers provide good geomorphic piercing lines to measure coseismic horizontal displacements. Most of the coseismic horizontal displacements we measured from offset young geomorphic markers range from 1 to 6 m on single surface breaks, and this yields an average sum of the horizontal displacement of 6–7 m (Figure 11). We also measured several larger offsets ranging from 12 to 21 m (Figures 11 and 16), but they should be the cumulative values. For instance, at the site E (35.760°N, 93.400°E), the surface rupture consists of two subparallel strands about 300 m wide. The northern strand offset small gullies on the young fans about 4 m in left-lateral sense. At this site we could measure a cumulative horizontal offset of ~12 m from the T_4/T_1 riser [*Xu et al.*, 2002b]. Similarly, at site *F* the last surface rupture offsets the young T_1/T_0 risers and small gullies only 4–6 m, while about 15 m or even up to 21 m for the adjacent older risers (T_2/T_1) and large gullies (Figures 11 and 16).

3.2. Along-Strike Variation of Coseismic Displacements

[28] The field measurements collected along the different sections of the rupture zone show large variation of the coseismic horizontal displacements associated with the 2001 Kunlunshan earthquake. Although the displacement is larger in the middle section on each section, the displacement curve is not bell-shaped, but it is rather characterized by several peaks of high displacements separated by low displacements (Figure 14).

[29] In summary, horizontal displacement along the western section is as large as 4.5 m and decreases to less than 1 m close to the Taiyang Lake. Along the transtensional section, although the observed surface rupture is very limited in length, the horizontal displacement is ~1.5 m. Along the eastern section, the displacement curve generally corresponds to the segmentation that was derived from the geometric characteristics of the rupture. Along the Hongshuihe subsection the horizontal displacement is rather constant with an average displacement of ~3.5 m. The maximum displacement reported along this section is 5.7 m [*Dang and Wang*, 2002], but this value is almost two times larger than those nearby. So, we prefer a maximum horizontal displacement about 4.5–5 m that we measured at a site (35.899°N, 92.096°E) for the Hongshuihe subsection. Along the Kusaihu subsection, a first large peak is observed with a maximum horizontal displacement of ~7.2 m. This subsection is characterized by the double fault strands resulting from the slip partitioning [*King et al.*, 2005]. Along the northern strand, the normal faults exhibit vertical displacement in the order of 0.5–1 m. Along the Yuxi Feng subsection, the horizontal displacement bursts with the maximum one of 7.6 ± 0.4 m, the largest value measured along the entire rupture zone. Nowhere could we find evidence for the 4 m vertical displacement reported by *Chen et al.* [2003]. This large displacement could correspond to misinterpretation of apparent vertical motion related to large horizontal offset [*Lin et al.*, 2004]. The eastern subsection (Yuzhu Feng) shows displacement up to 4 m decreasing gradually eastward. A clear thrust component has been identified along this subsection with a vertical reverse motion as large as 0.7 m [*Xu et al.*, 2002b].

[30] Thus the coseismic horizontal displacement curve associated with the 2001 Kunlunshan earthquake is characterized by six peaks corresponding to the different subsections (Figure 14). This displacement distribution is clearly consistent with other displacement distributions derived from InSAR by *Lasserre et al.* [2005] and from optical correlation by *Klinger et al.* [2005].

4. Faulting Segmentation and Subearthquakes

[31] Description of fault segmentation originates in the common observation that large faults usually do not rupture along their entire length in a single earthquake [*Schwartz and Coppersmith*, 1984; *Zhang et al.*, 1991]. Geometric discontinuities along faults have long been considered as barrier that can delimitate individual fault segments and possibly stop the rupture propagation [*Aki*, 1979; *King and Nabelek*, 1985; *Depolo et al.*, 1991]. On the basis of field survey and satellite image interpretation the surface rupture zone of the Kunlunshan earthquake can be divided in three main segments, the western strike-slip segment, the transtensional segment and eastern strike-slip segment. The eastern strike-slip segment itself can also be split in 4 subsegments as shown by the slip distribution.

[32] In the case of the Kunlunshan earthquake, the connection between the different segments is always associated to some obvious geometric asperity. The Taiyang Lake that separates the western strike-slip segment from the transtensional segment is clearly located in a pull-apart basin that makes the transition between the two strike-slip segments [*Klinger et al.*, 2005]. Such a pull-apart basin could possibly stop a propagating rupture [*Harris and Day*,

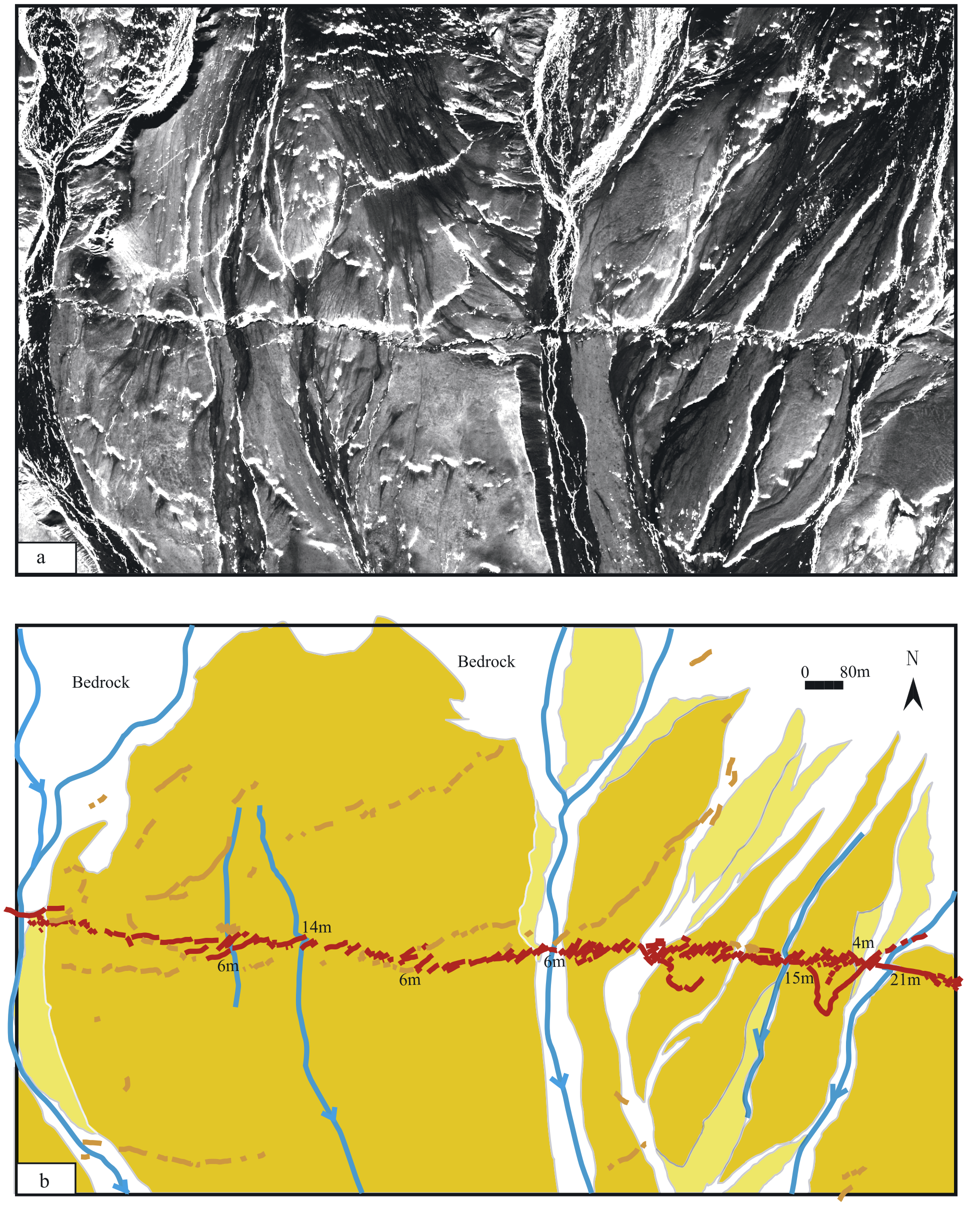

Figure 16. (a) Ikonos image created on 6 January 2003 that covers the area where *Lin et al.* [2002] gave a coseismic horizontal displacement of about 13.5 m. (b) Detailed strip map showing the surface rupture pattern of the Kunlunshan earthquake and coseismic horizontal displacements on different rupture strands. The legends are same as Figure 15.

1993, 1999] although in the case of the Kunlunshan earthquake the pull-apart basin was rather the starting point of the rupture. The connection between the transtensional segment and the eastern segment is marked by a bend of the rupture of ~20°, which could also be considered as a major geometric asperity.

[33] The length of each segment is quite different. The western strike-slip segment is about 26 km long, the transtensional segment is about 18 km long and the eastern strike-slip segment is about 350 km long (Figures 1 and 14). Using the relation between the moment magnitude (M_w) and the surface rupture length (L), $M_w = 5.02 + 1.19\log L$ [*Wells and Coppersmith*, 1994], the magnitudes associated to the western segment, the transtensional segment and the eastern segment are M_w6.8, M_w6.2 and M_w8.0, respectively.

5. Conclusions

[34] The 2001 Kunlunshan earthquake surface rupture zone has a complicated surface rupture pattern, involving primary and secondary breaks. The width of the rupture zone varies from few tens of meters to several kilometers. The main rupturing process is strike slip, accounting for ~350 km of surface rupture, although one subsection displays a fair amount of normal motion. We have shown that the maximum coseismic horizontal displacement is ~7.6 m with an average slip of 4–5 m. Larger displacement data

very probably correspond to measurement of cumulative offset. This interpretation is clearly consistent with other displacement distribution available for the Kunlunshan earthquake [*Lasserre et al.*, 2005; *Klinger et al.*, 2005]. Interestingly, the ratio between average horizontal displacement and the rupture length is rather low compared to similar size earthquake as the Denali earthquake ($M_w \sim 7.9$; 3 November 2002) whose rupture length is only 340 km, including a 48-km-long pure thrust rupture [*Haeussler et al.*, 2004]. This might be interpreted as the seismogenic crust being less thick in the Kunlunshan and therefore needing a longer rupture to achieve similar magnitude.

[35] These data are useful for reduction of earthquake hazard directly generated by surface faulting.

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